Benefits of Enhanced Data Quality and Visualization in a Control System Retrofit

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ABSTRACT

This paper discusses a recent innovative control system retrofit built with the aim of providing high-quality data and data visualization tools to the operator with the intent of using the information to improve operation. After eleven months of operation, comparing energy use to the previous four years gives savings estimates of 12% for electricity and 18% for steam use. Occupant comfort has also improved.

This approach to energy management differs from typical systems in that it is not black-box technology. Operators have the ability to use the information provided for fine-tuning control loops, reset schedules, and commissioning. The system includes high-quality sensors and high-resolution data collection to tighten control and ensure that the operator can fully trust the data he or she sees. The use of non-proprietary devices frees the operators from being tied to specific vendors, and the TCP/IP interface allows for greater freedom for normal, off-hour, and operator relief operations.

Trending and visualization are key. All data points, and most calculated points are trended and archived at up to one-minute intervals. Data visualization tools have been provided to the operator to view real-time and historic data in a manner not typically found in building automation systems. Metrics gauge operation in both text and graphic-based form, including time series and plots formed "on-the-fly". Trending of control parameters from the existing data files, creates profiles for flexibility and better start-up routines. Other uses of the high-resolution data include decreased system time to turn-over the system to the operators, with more emphasis placed by operators on system commissioning and heat balance of the air, water, and control systems. It also provides the information needed to justify savings opportunities in future equipment upgrades.

Background

The IMDS

The site of this retrofit is unique in that it was selected as the pilot demonstration site for a monitoring and diagnostics project led by Lawrence Berkeley National Laboratory (LBNL), known as the Information Monitoring and Diagnostics System, or IMDS. Several papers have been published describing the publicly-funded stages of this project which ended in December 1999 (Piette, et.al, 1998; Piette, et al. 1999, Piette, et al., 2000). As a research project, the IMDS was designed and installed independently of the existing control system and did not incorporate control features. In 2001 a major controls system retrofit was completed which was based on the monitoring technology and philosophy of this project. This paper addresses the controls retrofit undertaken by the building management as a result of its participation in the IMDS project.

The IMDS grew out of an initiative begun in 1992 to create a series of tools to assess life cycle costs and highlight performance metrics in Commercial buildings. Existing control systems as commonly installed and configured provide operators and property managers with extremely limited capability to measure energy performance, diagnose mechanical problems, and identify long-term cost-effective savings strategies. Sensor quality in many commercial control systems is typically poor and thus operators have limited faith in the data they do have. Even with credible data, good data visualization tools and methods are needed to utilize and understand the data. The IMDS provided continuous high-quality high-resolution data in tandem with data visualization capabilities not typically available to operators of commercial office buildings, and the primary goal of the IMDS research was to demonstrate this information could be used to reduce energy use by 15-30 percent through improved operational and maintenance practices.

In the short period of the project, many savings opportunities were identified, but with the burden of implementing the savings measures on the building staff and the reality of commercial buildings operation, no significant savings were realized in the duration of the research. A reduction in energy was noticed soon after the new IMDS-based control system came online in early 2001 and the building staff and controls contractor started using the new IMDS-based control system to tune operation. These savings were in addition to the savings opportunities previously identified in the research.

Operator Perspective

The IMDS was well received by the building operators and technical staff (Piette, et al., 1998). LBNL identified a number of potential energy savings opportunities (Piette, et al., 1999). In reviewing these recommendations, the operators considered implementation in the context of the on-going modernization of the building and the planned capital improvements. Many of the recommendations, and findings by the operators and technical staff, suggested that control changes needed to be made at the EMCS level. A major consequence of the IMDS project was an increasing level of frustration with the existing EMCS and the other layers of control systems: the lack of documentation, the proprietary nature of the top level control and monitoring, and the inappropriate control strategies that became obvious through data visualization.

A key component of the IMDS project was to involve the building operations staff in the research and have the operations staff actively participate in the IMDS installation. Thus when the research funds lapsed the building staff was used to the data acquisition and analysis capabilities and wanted to see those features extended into a new control system which was slated for an upgrade. While the existing EMCS was not very old (approximately 10 years), some components were beyond their useful life. A critical example was the operator interface that required an 80286-based PC and a custom, proprietary interface card. Repairs, and necessary upgrades to the existing EMCS were priced, and approximate capital costs totaled approximately $60,000 to $80,000 (Smothers, 2000).

Building Description

This retrofit took place at 160 Sansome Street, a Class A commercial office building located in San Francisco. Constructed in 1966, it has approximately 100,000 square feet of rentable space, including 8,000 square feet of commercial space on the ground floor and commercial office space in the remaining 17 floors. The central plant consists of two 1966-vintage chillers with 175-ton capacity, each with dedicated chilled and condenser water pumps. A two-cell forced-draft cooling tower provides heat rejection to atmosphere. Heat is provided by district steam, via two parallel heat exchangers. The ventilation system is a typical single-duct terminal reheat design of the middle 1960's. Two main ventilation systems provide conditioned air to the main floors and a smaller system to the bank area. A floor-by-floor retrofit has been underway for several years which includes conversion from constant air volume (CAV) to variable air volume (VAV) distribution, in addition to asbestos abatement, sprinkler installation, and fire/life-safety upgrades. Nine floors had been renovated at the time of this study.

Pre-Retrofit Control

The original control systems were a combination of pneumatic temperature control and an electro-mechanical control system for all equipment start/stop. All plant temperature sequencing was, essentially, "hard-wired" into the pneumatic/relay logic. In the thirty-five years since original construction, most of the control diagrams for the two main relay panels were lost. Additional mechanical time-clocks were added in various places, at various times, with no documentation of the wiring, and only handwritten labels that occasionally indicated the purpose of the time-clock.

The EMS retrofit in 1989 consisted of the addition of a Johnson Controls DSC 8500 controller with EP transducers to provide temperature control of the fans and dampers. Start/stop logic was implemented by finding the easiest place to locate a relay (as opposed to controlling the motor contactor directly) in the existing electro-mechanical relay logic. The chilled water plant was controlled by one relay that signaled the need for plant operation, the existing pneumatic/electric controls provided chiller sequencing and the chiller loading and temperature control were manual. A Barber-Coleman DDC controller was added in 1991 to provide static pressure control. It had independent start/stop control of the fans. As of 1992, there were three control systems that had to work simultaneously to operate the fan systems. While newer energy management systems do provide better control features than this, this description is not unusual for older buildings.

A New EMCS

In December of 1999, the operators and managers of 160 Sansome began requesting bids for a new energy management system. A basic functional specification was developed that assumed the functionality of energy management systems commonly available to the commercial building market. Additional requirements directly reflected the impact of the IMDS project:

> "There are three key elements of additional functionality that are a requirement of this bid: abandonment of the trend log metaphor in favor of a data acquisition metaphor, a time-series graph output in place of a "system graphic", and remote system access and control using any current web browser software.

"To implement a data acquisition metaphor, the new EMS must gather and store all digital and analog points at operator selectable data rates. The accumulated data files must be downloadable to an IBM-compatible PC in a format directly accessed by MS Excel (*.csv is acceptable and intended). The system will be capable of storing and accessing a minimum of 18 months of data at any time. KWP's intent is that all data be gathered at one-minute intervals for the main data archive, with the capability of logging any single datum at one second sample rates for a minimum of five hours, or up to four data points at one second sample rates for one hour.

"The main operator display will be a graph of data, with time as the X-axis and up to eight operator selectable points plotted on the Y-axis. The operator will be able to specify groups of points to be displayed "on-the-fly". An example of the minimum functionality required is the two-dimensional display capability of the software provided as part of the IMDS project. KWP is <u>not</u> looking for pictures of the building systems with point values pasted on the picture.

"Remote access to the system will be provided by web-based software." (Smothers, 1999)."

A presentation to building ownership outlined the cost of repair to the existing EMCS, the incremental cost for a new EMCS, potential energy savings, and the probability of a one year payback based upon the incremental cost; ownership concurred with the recommendation (Smothers, 2000).

Initial Control

The task of developing an open system to be phased into active operation to ensure that tenants and equipment were not impacted was done by a series of implementation steps and testing control routines via software. The core of the system is an electronic and relay-based system that interfaces directly with the controlled equipment. Many equipment options available to the previous control system were not used or split between two control systems, limiting opportunities for optimization. The IMDS software and the new EMCS software were used to start up each portion of the system. The core routines and inputs were developed using schedules and programming logic that were tailored to each system area and available sensors added by the IMDS and retrofit. The sensor accuracy gave the operators confidence to allow more refined dead bands and tighter, more repeatable, control. Once the base control was tested, the second level of programming started with the building operator and contractor. Because of the open nature of the system and its programming, the building operator was able to fine tune, and more readily, test any changes above the base programming. The documentation was maintained and several different logic revisions have been implemented and tested. The needs of the building were also defined using the previous EMCS and IMDS data and research project suggestions.

Adjustment of Operating Parameters & the Visual Interface Metaphor

Inherent in the implementation process was the assumption that the operators would have full control of operating parameters such as temperature lock-outs, reset schedules, and time-schedules. Basic control loop tuning parameters were supplied by the contractors; the operators then assumed the function of control loop tuning.

The time series graphs, as a primary operator interface were critical to the operator commissioning process. A standard display of numeric values, and a graphic display with overlaid values, shows only the current state of the building and systems. In addition, these displays are typically fixed (in terms of the grouping of the data) at the time of installation and are rarely changed during the life of the EMCS. (An exception is major system retrofits.)

The time series graphs have several advantages. The first of these is that a building and its' systems are dynamic and changing in time. The graph display provides the current value, and from the data archive, the past history, and the current trend. The trend of the data is of high importance to the operators. Secondly, the operator can select a significant subset of any system points to display. This means that the operator can determine which points are relevant at that instant, and concentrate on the <u>dynamic</u> relationship between the various system data points. The third major advantage is that the graphs can make use of historic data, and allow the operator to search the history for the points of interest/similar operating conditions, and to then compare the operation in the past to the present.

The remote web operation, also with time-series and X-Y graphs, was used extensively to monitor results of the optimum start, heat exchanger tuning, and warm-up parameters. There is no engineer on-site during much of the early morning start; remote viewing and control was used for both monitoring and control in fault conditions.

Control loop tuning. The tuning sequence for the various control loops was chosen ad hoc by the operators; as was the method. Integral and derivative gains were set to zero, proportional gains were adjusted to achieve reasonable performance in the operator's viewpoint. There was no formal mathematical method applied, the procedure was strictly trial and error. Several efforts to improve control by implementing integral gain failed, due to operator misunderstanding. In late summer 2001, LBNL's Commercial Building Systems Group provided the necessary corrections that allowed the building operators to successfully implement integral control, still trial and error, but a substantial improvement in accuracy (Haves, 2001). VFD loops on the supply and exhaust fans are the only loops that have not yet been adjusted by the operators. The operators used the time series graphs to view set-points, offsets, and one second time-series data to confirm results from tuning parameter changes.

Temperature lockouts and reset schedules. The ad-hoc nature of the building operators' efforts in the commissioning process was well illustrated by the adjustments to various lockouts and reset schedules. The operators checked temperatures and schedules based upon the weather conditions. Chilled water and cooling temperature adjustments were neglected until the outside conditions required cooling. Heating was considered and adjusted only when required by outside conditions.

The operators relied heavily upon real-time time-series graphs for schedule and set-point adjustments. The basic procedure utilized was simple - if the return air temperature is rising, too much heat is being added, if the return temperature is going down, not enough heat is being added. This is one example of using the visual trend of data as opposed current data only.

To adjust the supply air temperature reset schedule, the operators waited until neither artificial heating nor cooling were required. They then set the supply air temperature (SAT) for zero rate of change in return air temperature, while space temperatures were maintained within comfort limits (as shown by separate, simultaneous temperature graphs). After determining the required SAT at several outside air temperatures, an approximate line of regression between outside air and supply air temperature, became the final reset schedule. Immediate feedback is available from the time series data. Verification of proper reset schedule performance was completed by X-Y graph displays of actual data, confirming end-to-end system tracking of the desired reset schedule.

Examples

The installation and commissioning of the new EMCS was begun in late 2001, and was nearing completion in March, 2002. Because of the ad hoc nature of the operating staff's commissioning efforts, there was no formal program documenting the changes and the timing of the changes. The EMCS logic was backed up periodically to capture pre and post conditions. Operators frequently looked at the displays, compared data with previous operation, made adjustments on the fly, and monitored the graphs to see the effects of the changes. The following are some descriptive examples of the operator efforts. All figures are taken directly from operator displays, either local or on the web.

Supply Air Temperature Control and Reset

With the old EMCS, supply air temperature was controlled at a fixed set-point of 62° F. Heat exchanger temperature for heating ranged between 160° F, and 190° F. Figures 1 and 2 illustrate typical day operation. Building startup time was fixed, and difficult for the operator to change reliably. The upper curve is the return air temperature (RAT), middle is the supply air temperature (SAT), and the lowest is the outside air entering the fan. No heat exchanger data was available on the IMDS, but the temperatures were in the range stated above.

Figure 3 shows both SAT and hot water control, early in the installation and commissioning. The SAT was at a fixed set-point of 62° F, and the hot water supply was still at a high reset schedule. The heat exchangers shut down on return air lock-out at about 10:30 and 13:00. Figure 4 contrasts the change in supply air and hot water supply temperatures. With the new reset schedules, the SAT varies from 66 to 58.5° F, as the outside air varies from 50 to 105° F. The hot water varies from 160 to 110° F as the outside air ranges from 44 to 60° F. This allowed the economizers to provide more of the heating requirement, and reduced the load on the heat exchangers.

Figure 1. Old EMCS, Colder Day SAT

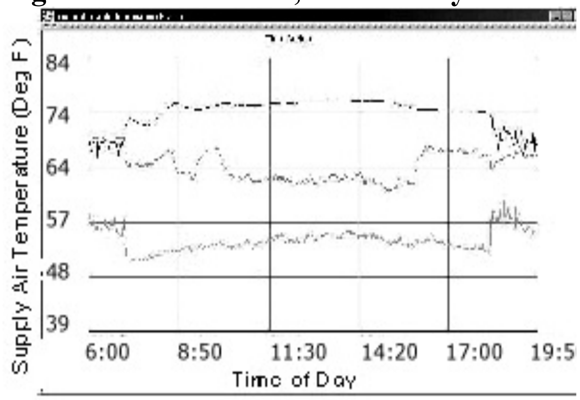


Figure 2. Old EMCS, Typical SAT

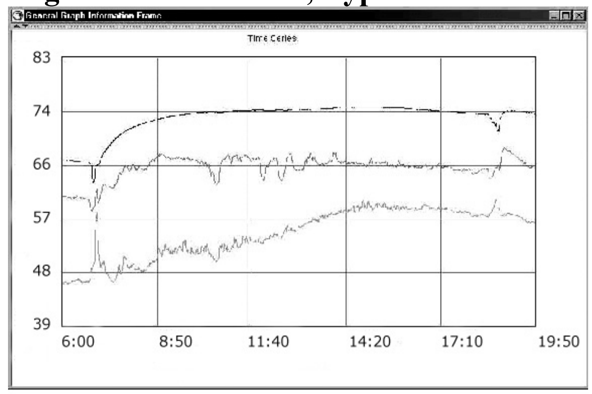


Figure 3. New EMCS, Old Resets

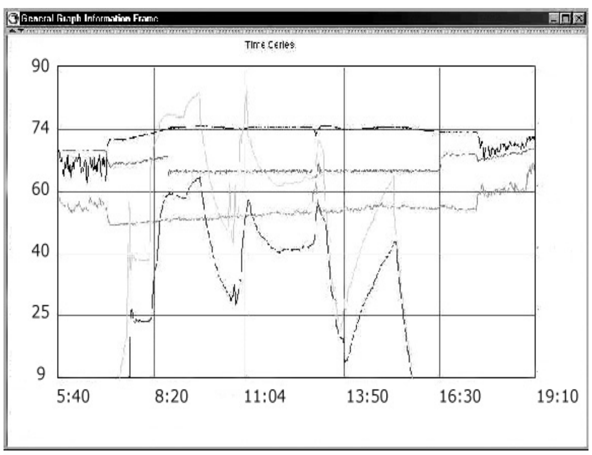
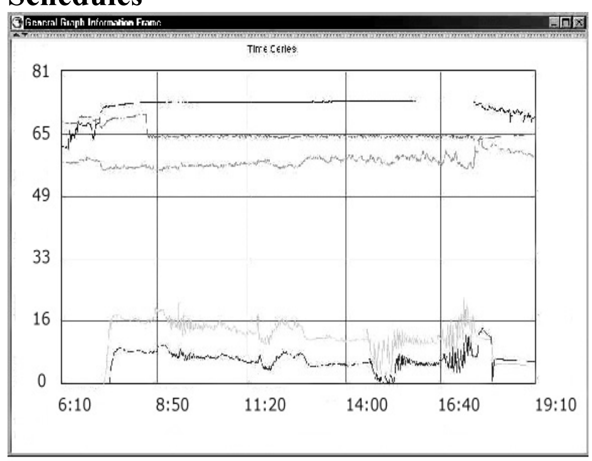


Figure 4. New EMCS, New Reset Schedules



The important thing to note in these four figures is that a key point for the operators was that if the time-series data appeared to fluctuate by large amounts…..something wasn't right.

Steam Valve Replacement

As heat exchanger data became available in April 2001, it became clear to the operators that steam control-valve leakage needed to be addressed. The data analysis software provided the necessary data to demonstrate the payback from a replacement of the steam valves. Figure 5 shows steam condensate flow over a two day period. Condensate flow is calculated based upon a differential accumulation every five minutes. Zooming in on the night time (heat exchangers off), and asking for a statistical an analysis yields Figure 6.

Figure 5. Steam Condensate Usage

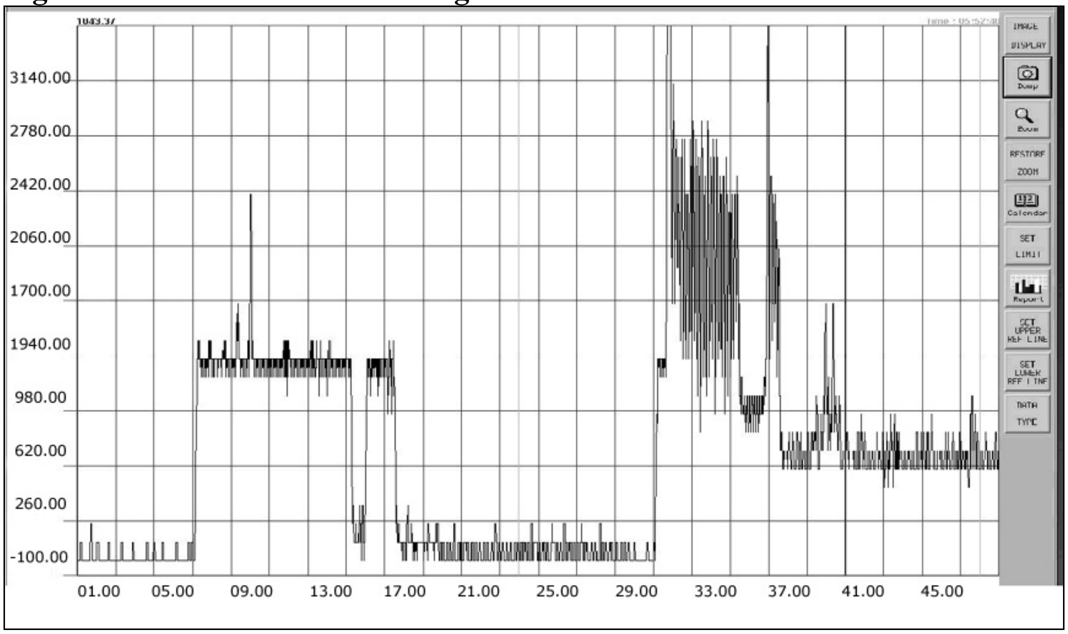
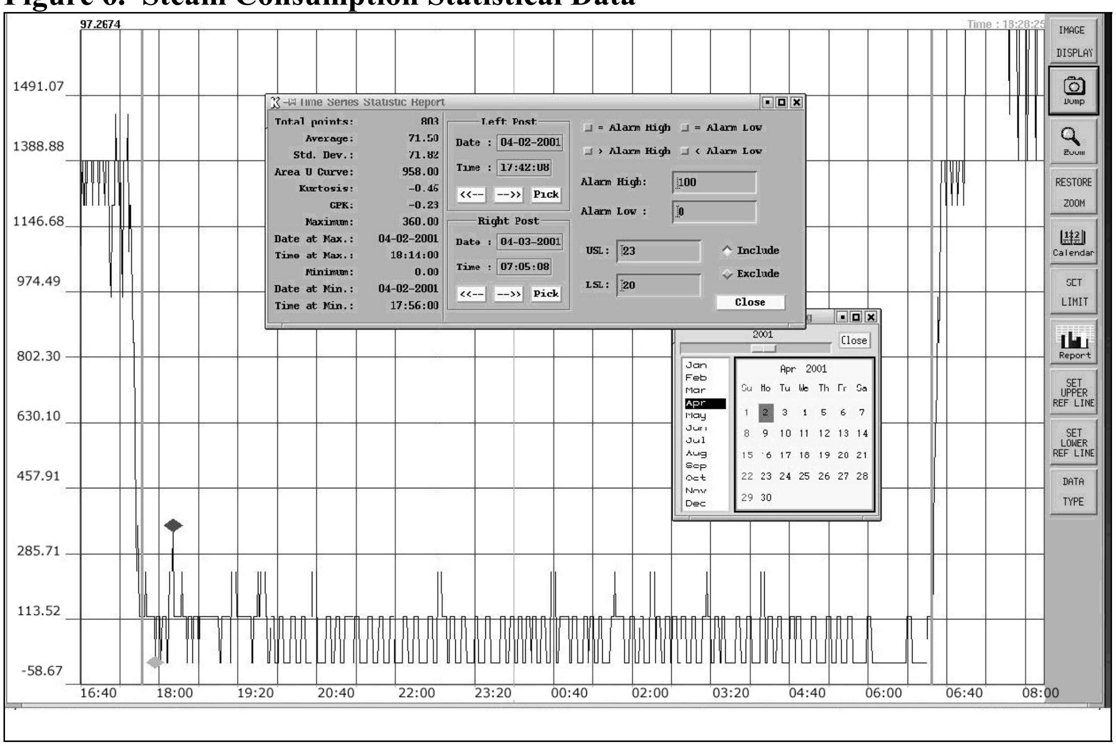


Figure 6. Steam Consumption Statistical Data



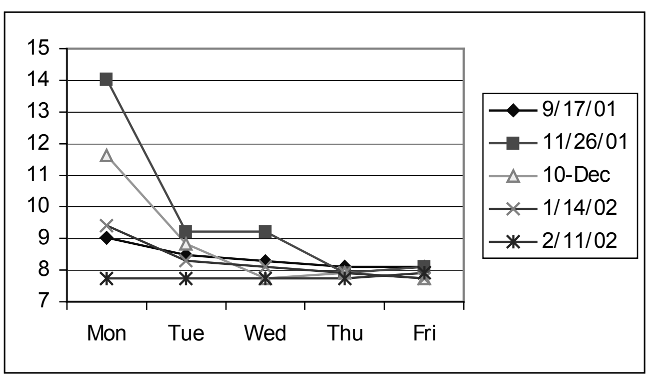
The data sheet shows starting and ending times for the analysis, average, standard deviation, maximum, minimum, and the area under the curve. The area under the curve is the steam consumption between the starting and stopping times. In 13.38 hours, 958 pounds of condensate leaked past the steam valves. At an approximate cost of $20.50 per thousand pounds of condensate, this equates to a leak cost of $1.46 per hour. Replacement valves cost approximately $1,503.00. This demonstrated a less than one year payback, even if the leakage was only reduced by one-half. This particular type of control valve does not provide positive shut-off, and, in real-world conditions, requires frequent re-build or replacement. The analysis easily quantifies the costs of steam loss in re-build, replacement, and system re-design scenarios.

Building Warm-Up

Both the old and new EMCS included warm-up strategies. These specified that if the return air temperature was less than a certain set-point (operator selectable with the new EMCS) the supply fans would use minimum outdoor air (approximately 25%). At the onset of relatively cold outside air temperatures in November and December of 2001, tenant complaints rose significantly. The heat exchanger reset schedules appeared to work properly to balance the heat-flow, but could not warm the building from a cold weekend. The San Francisco climate is so moderate, that only with fine tuning of the reset schedules, would a heat exchanger warm-up be required

On December 27, the operators made a major change to the control sequences, by adding a warm-up sequence for the heat exchangers. The strategy implemented was to add a reset schedule based upon return air temperature that would be used whenever the return air temperature was below an operator selectable value. The reset schedule was a cubic equation varying the hot water supply temperature from 170-140° F as the return air temperature changed from 68-73° F. The cubic equation was chosen to hold the hot water temperature high over a range of return air temperatures, while still bringing the hot water temperature closer to normal as the return temperature approached normal values. Figure 7 shows the time of day that the building exited warm-up mode for several representative weeks. As can be seen, the November and December weeks showed poor performance on Mondays, and barely acceptable performance on Tuesdays after a cold weekend. Performance was substantially improved in the January and February examples.

Figure 7. Warm-Up Exit Times as a Function of Day of Week

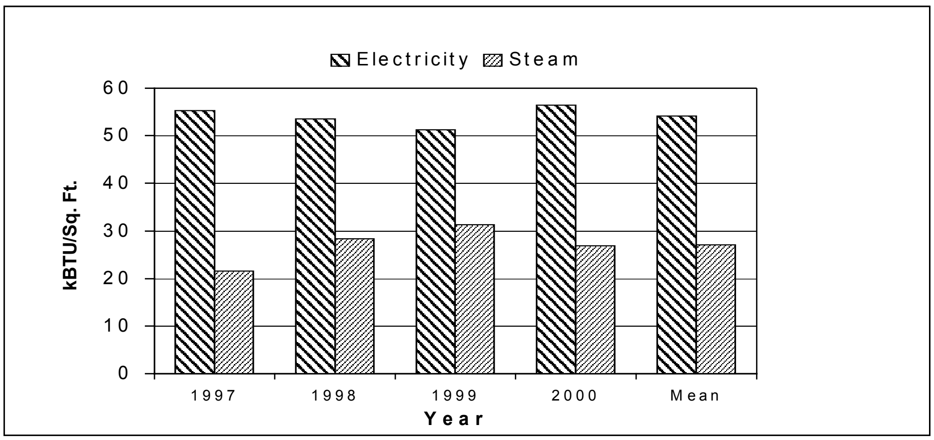


Results

Energy Usage

The management of 160 Sansome Street has tracked monthly utility billing since July 1990. The data tracked included monthly energy usage (kWh), peak demand (kW), steam usage (lbs), and electric and steam costs. Figure 8, below, shows the energy data expressed in kBTU/sq. ft./yr, based on 95,200 net rentable square feet. Mean usage over the last four year period was 54.13 kBTU, electric, and 27.03 kBTU, steam.

Figure 8. Historic Energy Usage, 160 Sansome Street, San Francisco



Long-term energy use has been affected by a number of changes in occupancy, modernization, and lighting retrofits. Since 1996, other than minor savings achieved and described in the IMDS results (Piette, et al., 2000), the EMS retrofit represents the only major change in energy usage.

Initial control of building systems via the IMDS-based control system was established in late February, 2001. The first energy bills available for comparison purposes are those of March, 2001. Table 1 below, outlines the energy savings for the first eleven months of operation. The past four year data represents the average usage for the same eleven months for the previous ten years.

Table 1. Energy Consumption—Before and After

	Electricity (11 Months)	Steam (11 Months)
Past 4yr Average	1,389,400	1,889,518
Current Usage	1,219,600	1,537,840
Savings	169,800	351,678
Percent Savings	12.22%	18.61%
Annualized Savings	185,236	383,648
Annual Savings @today's cost	$30,903	$8,964

Occupant Comfort Measures

Until June 25, 2001, the records of tenant HVAC calls were on paper and incomplete. Piette et al. reported between three and 21 HVAC calls per month based on sixteen months of these records (2000). Since June of 2001, all tenant calls have been tracked on a computerized tenant work-order system. In the eight month period ending February 28, 2002, there were nine calls reporting "too cold" and four calls "too hot"; less than 1.5 calls per month. Since completion of the warm-up changes in January 2002, there have been no tenant comfort calls.

Future Work

While the EMCS retrofit provides plant- and system-level control, all VAV and CAV zones are still pneumatically controlled. Zone temperatures reported on the new EMCS indicate that several of the individual temperature control zones need re-balancing, or thermostat/zone-controller re-calibration. This is indicated by significant deviation from the average zone temperature. The operators of the building plan to perform an air-side balance and calibration of the VAV zones in 2002.

A chilled water plant upgrade was in the capital budget in fiscal year 2002. This has been postponed due to other capital requirements. The data on building cooling demand versus outside air conditions is gathered and archived once per minute continuously; there are now four years of monitored data available. This will be a valuable resource in properly sizing the new chilled water plant, currently scheduled in the FY 2004 budget. Interim projects under consideration is the automation of chilled water temperature control using the new EMCS and VFD control of the cooling towers.

Conclusion

The new EMCS at 160 Sansome has been highly successful. It has met its targets for energy conservation and improved occupant comfort. Because the operators were directly involved in the development and commissioning of the system, there is a much higher level of operator understanding of both building and system function. The data archive capability has provided both direct real-time and past history comparison of performance data. The data archive capability, along with the data analysis software provides direct data for operational and capital improvements.

The system has also enabled a continuing cooperation between the LBNL Commercial Building Systems group and the building operators. Building performance data is still being supplied to LBNL, and will soon be transferred automatically on a daily or weekly basis. As a direct result of this cooperation, there is also ongoing work with MIT in their research into non-invasive load monitoring.

The project that started as a simple "Information Monitoring and Diagnostic System" has grown into a complete energy management system and a platform for further research specific to 160 Sansome and to commercial office buildings in general.

Acknowledgements

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